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Microgrid Modeling and Simulation Study

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by Edward C Shaffer, Steven L Kaplan, and Donald H Porschet
Sensors and Electron Devices Directorate, ARL

Denise Hanus and Darrell Massie
Intelligent Power and Energy Research Corporation
Fort Montgomery, NY

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14. ABSTRACT

This report describes a survey of modeling and simulation (M&S) efforts that are related to tactical microgrids. Based on this survey, the most relevant M&S projects have been identified and compiled into a coherent database to provide a “roadmap” for the US Army and Department of Defense (DOD). This roadmap will be used to guide DOD M&S strategy and planning, as well as develop a comprehensive microgrid M&S capability and prioritize future efforts. Analysis of current microgrid M&S research is presented, and specifics of the different projects related to tactical microgrids are compared. The results were then used to identify gaps in existing tactical microgrid M&S research. This work was funded by the US Army Research Laboratory and performed by Intelligent Power and Energy Research Corporation.

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microgrid, modeling, simulation, tactical, distributed, energy, power

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Study

The purpose of this study was to perform a modeling and simulation (M&S) gap analysis relevant to tactical microgrids. The outcome of the analysis was a list of M&S projects that will enable the US Army and Department of Defense (DOD) to align their M&S focus, develop a balanced microgrid M&S portfolio, and prioritize investments. The project involved a 4-month effort to analyze current microgrid M&S research, compare the efforts to specific enablers for tactical microgrids, and identify gaps in tactical microgrid M&S research. The study was funded by the US Army Research Laboratory and conducted by a private contractor (Intelligent Power and Energy Research Corporation).

Background

A microgrid is an integrated energy system consisting of an intelligent management system with control features that allow stable integration of multiple energy sources, loads, and storage on the electrical grid in either islanded or grid-connected mode. Energy surety is provided by prioritizing service to critical loads. Using a coordinated and common interface, a microgrid system promotes operational robustness through reconfiguration features that operate through loss of communications. In the current context microgrids are not

- small stand-alone hybrid/generation systems with individual component controls,
- power systems on stand-alone vehicles or aircraft, or
- renewable systems that are not generically reconfigurable.

Tactical microgrids are unique from utility-scale microgrids because of their smaller scale and the need for reliability, portability, and reconfigurability. These requirements drive Army and DOD investments that would otherwise not be addressed by industry or commercial products. Tactical microgrids can improve mission effectiveness, command visibility, and sustainability while reducing setup time, maintenance requirements, manpower requirements, logistical transport, and life-cycle cost.

Results

Results are summarized in a Summary Table that lists the technical capability (communications or electrical), enabling technology gap, investment priority, and whether the investment area would require a short- or long-term investment. The technology enablers necessary for advancing tactical microgrids were determined using the US Army Research, Development and Engineering Command (RDECOM) Power & Energy TFT Microgrid Technology Roadmap developed in 2011.[1] The 2011 roadmap was reviewed for applicability and relevance of key technology enablers. Next, a literature search and interviews of academia researchers, research organizations, and industry professionals were performed to identify current microgrid M&S tools. Each M&S tool was compared to the 2011 roadmap key technology enablers to determine if the M&S tool could be leveraged by DOD for the advancement of tactical microgrids. M&S efforts not applicable to tactical microgrid were discarded (i.e., utility-level M&S tools). The enabling technology areas that lacked overlap with the M&S tools were identified and used to generate a list of research gaps. Next, the identified research gaps were prioritized according to military needs, considering the requirement to balance technological advancements across all microgrid capability areas identified in the 2011 roadmap. Finally, using the current technology readiness level of each technology enabler, the time frame needed to advance each effort was categorized as short term or long term.

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[1] Shaffer E. Power and energy TFT microgrid technology roadmap. PowerPoint presentation. Aberdeen Proving Ground (MD): Army Research, Development and Engineering Command (US); 2011.

1. Introduction

Tactical microgrids are unique from utility-scale microgrids because of their reliance on portable power sources, such as diesel fuel-burning generators and hybrid systems. Tactical power must be portable, readily reconfigurable distribution systems, with primarily islanded operations and operating loads from tens to hundreds of kilowatts. Forward-operating bases must have a central power plant with possible opportunity for interconnection with a local utility grid and an operating load from hundreds of kilowatts to megawatts. Based on the findings of a 2014 Tactical Microgrid Study,[1] the Army must invest into the development of tactical microgrid technologies to support forces by providing improved reliability and availability of electrical power while reducing fuel consumption. Tactical microgrids can improve deployment logistics through reduced setup time and maintenance, thus reducing life-cycle cost for the military, improving mission effectiveness and command visibility, and reducing manpower requirements. Complex tactical microgrids require a new approach to testing and performance validation. Characterizing the relative performance of more complex systems requires modeling and simulation (M&S) to augment hardware tests. The Department of Defense (DOD) needs a software model that estimates the performance of advanced tactical power systems over a wide range of operating conditions, under a variety of configuration, and at hard-to-test edge conditions. These models must be supplemented with well-defined component-level tests to provide accurate input data for the model as well as system-level tests to validate the model's results. Both the simulation and the test procedures will inform future procurement decisions. A 2014 Tactical Power Systems Study[1] included several implementation recommendations related to microgrid M&S:

- Advanced energy equipment within an open architecture would enable interoperability between equipment from different vendors, encourage competition within industry, and facilitate future equipment modernization. In particular, the control methods, communication protocols, and power interfaces should be standardized in a vendor agnostic manner.

- A performance evaluation of hybrids or microgrids is a complex process and will require a standardized set of modeling tools. The DOD should invest in a standard model that can be used to compare system performance prior to making acquisition decisions.

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[1] Van Broekhoven SB, Shields E, Nguyen SVT, Limpaecher ER, Lamb CM. Tactical power systems study. Lexington (MA): Massachusetts Institute of Technology–Lincoln Laboratory; 2014 May 19. Technical Report No.: 1181.

- New test procedures for components and equipment should work in concert with the modeling tools to verify and validate the models and test-edge condition.

2. Project Scope

The US Army Research Laboratory (ARL) initiated an analysis of the existing state of modeling, simulation, validation, and verification for tactical and reconfigurable microgrids to identify gaps in current and proposed research related to M&S. The purpose of the analysis was to determine those projects that best enable DOD to align its research focus and prioritize its development efforts. The analysis was performed by a private contractor (Intelligent Power and Energy Research Corporation). Information pertaining to M&S was requested from national laboratories (Sandia National Laboratories, Oak Ridge National Laboratory, Idaho National Laboratory, Massachusetts Institute of Technology–Lincoln Laboratory, Pacific Northwest National Laboratory), the US Army Research, Development and Engineering Command (RDECOM) (Army Materiel Systems Analysis Activity [AMSAA]; Army Research Laboratory; Communications-Electronics Research, Development and Engineering Center; Tank Automotive Research, Development and Engineering Center), the Navy (Office of Naval Research, Naval Surface Warfare Center), the US Army Corps of Engineers (Army Engineer Research and Development Center–Construction Engineering Research Laboratory), and Interagency Advanced Power Group Steering Group members and panel leaders. In addition, a literature search of relevant sources was conducted (including the Defense Technical Information Center database, National Science Foundation awards, IEEE Xplore digital library, ScienceDirect.com, Scientific.net, and relevant academic research agencies). The papers, abstracts, reports, and research summaries were reviewed for relevance to tactical microgrid M&S; a list and abstract description of the reviewed documents are provided in Appendix A.

3. Analysis

The M&S tools were further characterized based on the different level of fidelity and different operational time scales. M&S allows the behavior of the tactical microgrid to be studied and may require different tools depending on the desired outcome. During the early technology readiness levels, system design trade-offs must be made to balance the cost of the grid versus its capability. Comparisons in fuel consumption and operating hours can be made against stand-alone power generation (spot-power) or other control strategies (spinning reserve, energy storage, renewables, etc.). Microgrid M&S for mid-technology readiness levels should incorporate more extreme testing. Surges in power demand, distribution faults, lightning, and other scenarios need to be simulated and hardware tested to characterize system robustness. The reviewed M&S tools were divided into the following categories:

- **Design and Planning Tools** are planning tools that do not require specific grid layout details. These models may be used to determine system design trade-offs to balance the cost of the grid versus its capability. Existing M&S tools include the following:
    - **DOD Operational Energy Decision Tools** address operational energy for tactical application planning. These tools are used to balance the cost of the grid versus the capability of the system design in early operational planning stages.
    - **Microgrid Design Tools** are models used to make a predictive recommendation on an appropriate mix of microgrid technologies. This type of modeling is used to evaluate system performance over long time durations (typically a year or more) while matching supply to demand over coarse time intervals. The outcome of this modeling is a predictive recommendation on an appropriate mix of technologies without detailed grid information.
    - **AMSAA Fuel Consumption Models** are tools that have been used in several studies to specifically evaluate fuel savings of various energy distribution technologies to apply to technology development and organizational changes. The AMSAA studies related to microgrids were static and nonreconfigurable; however, these fuel-use models are valuable because they have been validated using actual data and existing DOD equipment or commercially available technologies. For example, AMSAA has developed several "modules" for structures and environmental control units (ECUs) to generate data representing power consumption. Additional modules for power generation equipment calculate fuel usage for a load profile.
- **Microgrid System Optimization** involves examining how different types of technologies can be applied to meet high-level design goals. Information regarding the actual grid layout is required for this level of M&S. This type of analysis looks at system performance over long durations (typically a year or more) while matching supply to demand over coarse time intervals. The outcome of this analysis is a recommendation on an appropriate mix of technologies (photovoltaic, diesel generation, energy storage, etc.) and system architectures needed to meet high-level performance goals.

- **Load Flow Simulation** is the next level of fidelity, also known as load flow analysis. In this analysis, a specific power-grid layout is examined, and the flow of electricity on the grid is modeled. These models include individual sources and loads as well as cables and power-conditioning devices. The current and voltage at each major node are calculated for a variety of operating conditions, and the results are examined for conditions that could cause a grid disruption.
- **Transient Stability Analysis** is the highest-resolution power-grid simulation. These simulations include voltage and frequency control and must be accomplished over a short time frame (seconds to milliseconds). Very high-fidelity models must be created for all of the sources and loads on a given power grid.

4. Results

Tactical microgrids are uniquely different from utility and commercial microgrids. The technology requirements necessary to advance tactical microgrid technology (enablers) were determined using the RDECOM Power & Energy TFT Microgrid Technology Roadmap developed in 2011.[2] This roadmap identified 5 capability categories for tactical microgrids: Demand Management, Power Distribution, Source Management, Communications, and Smart Controls. In addition, the 2011 roadmap listed enabling capabilities necessary to advance each capability and the relative time frame necessary to develop each enabling technology. Some of the identified enabling technologies apply to multiple capability categories. Reviewers compared each M&S tool with these key technology enablers to determine if the M&S tool could be leveraged by DOD to advance tactical microgrids. If the M&S effort applied only to utility-based microgrids, then the technology enabler was not addressed. If the M&S effort could be applied to tactical microgrids, a tally was made for the key enabler that was addressed. The enabling technology areas that lacked overlap with the M&S tools were identified and used to generate a list of research gaps. An overview of this comparison for the 5 capability categories is provided in Appendix B.

The technology enablers that lack current research focus were reviewed to identify research gaps. Each specific enabler topic was reviewed, and the research gap necessary to advance tactical microgrid M&S was determined. Next, the list of research gaps was prioritized according to the military needs, considering the requirement to balance technological advancements across all 5 of the 2011

[2] Shaffer E. Power and energy TFT microgrid technology roadmap. PowerPoint presentation. Aberdeen Proving Ground (MD): Army Research, Development and Engineering Command (US); 2011.

roadmap capability areas. Table 1 summarizes the capability category, key enabling technologies, and comments regarding the specific identified research gaps. Using the current technology readiness level, we categorized the time frame needed to advance each effort as short term or long term. Short-term investments represent technologies that have a current readiness level that does not require a significant time frame to produce results, while those needing longer sustained investment are classified as long-term investments.

Table 1. Summary table

Energy and Power Capability & Sub-capability		Enabling Technology	Comments
High Priority Investments - in order of merit			
Demand Management	Plug Level	Information networking (wire mesh/PLC/others)	Necessary for a dynamic, reconfigurable, self-healing microgrid by allowing point to point communications without data cables (Long term investment)
Source Management	MILSTD: Legacy generators	Enhanced controls (prognostic and diagnostic)	Microgrid control is enhanced through access to real time P&D; however, the use of M&S for a cost benefit analysis is crucial to determining the real benefit of P&D technology. (Long term investment)
Source Management	Reduced Human Intervention	Self healing	Enabling technology to allow microgrid control logic to deal with equipment failures in an automated manner by implementation of programming contingencies and sequencing (Short term investment)
Communications	Peer-to-peer	Rapid send-listen techniques	M&S is needed to determine an approach for handling increased informaton in a low band width environments. Efficient protocols and techniques to handle latency issues must be addressed. (Short term investment)
Communications	Ad-Hoc Reconfiguration	Lost communication recovery	Technologies that enable microgrids to operate through periods of lost communication. Techniques must be efficient and prioritize information for timely asset coordination. (Short term investment)
Demand Management	Distribution Level	Energy deferral technology (storage)	Highly distributed energy storage is necessary for the implementation of renewable resources. (Long term investment)
Moderate Priority Investments - in order of merit			
Power Distribution	Transient Management	Frequency/penetration of renewables	Current M&S efforts are focused on renewable energy sources for static utility grids with no observable effort made to determine impact on reconfigurable grids. (Short term investment)
Communications	Peer-to-peer	Mobile devices - integration/security	Large quantity of moblie devices and nodes that tie into a microgrid using a mesh network will overload the network and needs a communications security approach. (Long term investment)
Communications	Ad-Hoc Reconfiguration	Lost communication - reliability	Research is needed to make reconfigurable information networks more reliable in a constantly changing environment. (Long term investment)
Communications	Ad-Hoc Reconfiguration	Mesh Networking	The structure of the microgrid network can directly affect the transmission of data (i.e. issues with frequency, signal length, EMF); M&S will identify robust technology options (Long term investment)
Smart Controls	Components	Component metadata	Implementation of metadata may offer opportunities to reduce complex problems in reconfigurable grids (Short term investment)
Power Distribution	Energy Storage	Vehicle to grid	Potential for tactical applications requires M&S investment to understand dynamic behavior of vehicles relateive to generators and energy storage. (Long term investment)
Power Distribution	Transient Management	Fault Identification and isolation	Modeled by many utilities for power distribution capabilities; however, tactical grids typically operate in low voltage/high current states and leveraging high voltage utility efforts may not be applicable. (Short term investment)

Collectively, the 2011 roadmap and this M&S study provide the Army and ARL with a gap analysis as well as M&S investment priority recommendations. Based on a review of the existing and proposed M&S efforts, the following broad categories of enablers were identified as high-priority research needs for DOD:

- **Prognostics and Diagnostics (P&D):** The investment of sensing devices and simple-to-implement algorithms within microgrid equipment that allows affordable yet useful P&D is a Source Management capability. Microgrid control is enhanced through access to real-time P&D; however, the use of M&S for a cost-benefit analysis is crucial to determining the real benefit of P&D technology. The current readiness level of P&D requires a long-term investment to produce results.

- **Self-Healing** is an enabling technology that allows the microgrid control logic to deal with equipment failures in an automated manner by implementing programming contingencies and sequencing. Self-healing technology is a Source Management capability, and the current readiness level requires a short-term investment to produce results.

- **Communications:** In the tactical microgrid, a communication link is required to handle high-latency supervisory command and control, and health and status monitoring. All communication layers—the physical/data link layer, the transport layer, and the application layer—must be standardized. Within the Communications capability, there are 3 high-priority enabling technologies:

    - **Mesh Networking** is a network topology in which each node relays data in a flexible distributed architecture and is a subcategory within Communications. This enabling technology is necessary for a dynamic, reconfigurable, self-healing microgrid by allowing communications to go from any point within the network to another point. The structure of the microgrid network can directly affect the transmission of data (e.g., issues with frequency, signal length, and electromotive force), and M&S can benefit the development of technology options. Work by the Navy, involving bus rings with a high number of nodes, may be applicable to this effort. The current readiness level of mesh networking requires a long-term investment to produce results. Mesh-networking is also an enabler necessary for Demand Management in a tactical microgrid network with interconnected grids.

    - **Rapid Send-Listen Techniques** is a specific enabler necessary for communications in a reconfigurable microgrid. The network communication standard and latency of various technologies are issues that would benefit from M&S and follow-on test-bed efforts. The current readiness level of rapid send-listen techniques requires a short-term investment to produce results.

- **Lost Communications** includes recovery and reliability. **Communication Recovery** technologies that enable microgrids to operate through periods of lost communication require M&S to assess the benefits/drawbacks. The current readiness level of Communication Recovery requires a short-term investment to produce results. Finally, **Communication Reliability** technologies that enable microgrids to prevent lost communication are important; however, the priority level of communication loss prevention is lower than other technology enablers listed previously because of the low probability of loss prevention in a fielded microgrid.

  Energy Deferral/Storage is a limiting technology necessary to implement renewable resources in a microgrid. Current and planned M&S research does not adequately address energy storage opportunities implementable within a tactical grid. The current readiness level of energy storage requires a long-term investment to produce results. Energy storage is an enabler necessary for Demand Management and Power Distribution capabilities. In addition, the opportunity to use electric vehicles as bi-directional power (energy storage) requires greater evaluation; however, the priority of energy storage in V2V/V2G is lower than other technology enablers listed because of the uncertainty of electric vehicle use in tactical microgrid applications. The following enablers were identified as moderate priority research needs for DOD:

- **Transient Management and Power Flow** has been modeled by many Utilities for Power Distribution capabilities; however, tactical grids typically operate in low-voltage/high-current states, and leveraging high-voltage utility efforts may not be applicable. There have been some DOD efforts to incorporate network nodal overload analyses to determine optimum power grid architecture (e.g., path redundancies) given variability in the demand location (AMSAA high-power simulations). However, these simulations are designed for a specific network/power demand. M&S that allows other system topologies would be beneficial to tactical microgrids. The current readiness level of transient management and power flow technologies requires a short-term investment to produce results.

- **Component Metadata** is the use of digital information from equipment for microgrid Smart Controls capabilities. The object model, or parameter list, for each device type must be standardized to enable interoperability. In addition, the implementation of metadata may offer opportunities to reduce complex problems in reconfigurable grids. The current readiness level of using metadata in microgrid equipment requires a shorter-term investment to produce results.

- **Communications:** Mobile devices used by Soldiers provide a unique opportunity within microgrids as a Communications capability. However, the problems associated with using many of these devices within the same microgrid and their effect on communications security are unknown. The current readiness level of using mobile devices in a microgrid requires a long-term investment to produce results.

5. Conclusion

The advancement of tactical microgrids requires M&S software that will operate over a wide range of operating conditions and a variety of configurations. Enabling capabilities necessary to advance tactical microgrids were identified in the RDECOM Power & Energy TFT Microgrid Technology Roadmap.[2] Existing research and software tools related to modeling, simulation, validation, and verification were evaluated against the identified enabling capabilities contained in the RDECOM roadmap to determine research gaps. This evaluation was used to develop a prioritized list of M&S projects with consideration of the requirement to balance technological advancements. Prioritization of M&S projects will help enable the Army and DOD align their M&S focus, develop a balanced microgrid M&S portfolio, and prioritize investments.

6. References

1. Van Broekhoven SB, Shields E, Nguyen SVT, Limpaecher ER, Lamb CM. Tactical power systems study. Lexington (MA): Massachusetts Institute of Technology–Lincoln Laboratory; 2014 May 19. Technical Report No.: 1181.

2. Shaffer E. Power and energy TFT microgrid technology roadmap. PowerPoint presentation. Aberdeen Proving Ground (MD): Army Research, Development and Engineering Command (US); 2011.

Appendix A. Documents and Sources Reviewed

Because this appendix contains proprietary information, it has been published as a separate report, ARL-SR-0361.[1]

[1] Shaffer EC, Kaplan SL, Porschet DH, Hanus D, Massie D. Microgrid modeling and simulation study: appendix A. Adelphi (MD): Army Research Laboratory (US); 2016 Sep. Report No.: ARL-SR-0361.

Appendix B. Technology Enabler Summary

Demand Management

Sub-Category	Enabler	M & S Effort	Notes	Number of Identified Efforts
Grid Level	Economic dispatch	NO		9
	Price forecasted dispatch	NO	Industry solution; CERL support	0
	Smart-building automations	NO	Industry solutions	1
	Communications/interoperability	*	No for microgrids; yes for comms to soldier	3
			Standardards in place or evolving	
	CANbus/Modbus interoperability	YES		1
	Critical load assessment/prioritizat	NO		1
Distribution Level	Energy deferral technology (storage)	YES	No evidence of distribute energy storage outside of TARDEC	5
	Information security for distribution devices	YES?	ESTCP topics. ARL & CERDEC?	2
	AC/DC interoperability	YES?	ESTCP topics. ARL & CERDEC?	2
	EMS, BAS, Advanced Controls	YES?		1
	Meteorology input based response	NO	CERTS software;	3
	Load prioritization/load shedding	NO		2
	Phase balancing of DER	?	Not sure if this needs M&S; prototypes are available	1
	Integrate legacy electrical system	NO		2
	EMS, BAS, Advanced Controls	NO		0
Plug Level	Information networking (wire mesh/PLC..)	YES	Integrated, module, flexible distributed architecture required	1

Power Distribution

Sub-Category	Enabler	M & S Effort	Notes	Number of Identified Efforts
Inverter	COTS (use in military applications)	NO		4
Energy Storage	Battery chemistry	YES	input/output is important for modeling	1
	Vehicle to grid	YES	CERTS demonstration LA AFB	5
Transient Management	Power Flow/VAR	YES?		8
	Fault identification/isolation	YES	S&C Smart Grid Controls	2
	Frequency/penetration of renewables	YES	What penetration of renewables?	7
	Overcurrent protection	NO		3
Autonomous Grid Interconnection	CANbus/Modbus interoperability	NO	ESTCP topics. ARL & CERDEC?	1
	AC/DC interoperability	YES?		2
	Control/hardware interface	NO		3
	integration	NO	See "On board data fusion and decision tool" below	3
	Droop control	NO		7

Source Management

Sub-Category	Enabler	M & S Effort	Notes	Number of Identified Efforts
MILSTD: Legacy generators	Enhanced controls (prognostic and diagnostic)	YES		2
	Interface compatibility	NO		3
	CHP	NO	Leverage oil industry and emergency management	0
COTS Sources	Renewables: Grid stability	YES		5
	Renewables: on-board system	YES		2
Reduced Human Intervention	On board data fusion and decision tool	YES		3
	Self healing source mgmt structure	NO	S&C Smart Grid Controls	6
Automated Reconfigure	Grid Isolation	NO	S&C Smart Grid Controls	1
	Fault Discovery	NO	S&C Smart Grid Controls	1
	Automatic grid rebuild	YES		1

Communications				
Sub-Category	**Enabler**	**M & S Effort**	**Notes**	**Number of Identified Efforts**
PLC	Location detection	NO		0
	Electronic warfare/EMI	-		0
	Noisy environment - reliability	YES		0
	Lost communication - reliability	NO		0
	Component protocols	NO		0
	User/Component Authentication	NO		0
	Eliminate need for communication	NO		0
	PLC with location detection	NO	Prototypes in place	1
	COTS: wireless	?		0
	COTS: fiber optic	NO		0
Peer-to-peer	Sub-system auto tracing	NO?		0
	mobile devices - integration/security	YES		0
	rapid send-listen techniques	YES		0
	Electronic warfare/EMI	YES?		0
	Noisy environment - reliability	YES		1
	Lost communication - reliability	YES		1
	Lost communication recovery	YES		1
	Noisy environment - reliability	-		0
	GUI Training	NO		1
	Mesh Networking	YES		1
Ad-Hoc Reconfiguration				

List of Symbols, Acronyms, and Abbreviations

AMSAA	Army Materiel Systems Analysis Activity
ARL	Army Research Laboratory
DOD	Department of Defense
ECU	environmental control unit
M&S	modeling and simulation
P&D	Prognostics and Diagnostics
RDECOM	Army Research, Development and Engineering Command

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